Real Time Simulation of Power System and HIL Testing of STATCOM Based Inter-area Oscillation Damping Controller

Maya G., Elizabeth P. Cheriyan, Jeevamma Jacob

Abstract-- **FACTS controllers are found to be effective in improving transient stability of an inter-connected power system. This paper investigates the improvement of transient stability of an interconnected system using STATCOM which is a shunt FACTS device. The inter-area oscillations can be controlled by changing STATCOM's bus voltage angle and magnitude, hence regulating active power flow through the network. The control strategy is to be implemented in real time using Digital Signal Processor (DSP). The controller hardware-in-loop (HIL) testing will be done under conditions that are identical to those which will be encountered in the real power system. The control signal from DSP is fed back to the simulated system via DAC-ADC combination. In HIL testing of controllers, the actual controller is tested against a simulated plant model running in the real-time simulator.**

Keywords: **FACTS Controllers, STATCOM, HIL, Real time simulation, inter area oscillations.**

I. Introduction

THE electromechanical oscillations between inter-connected area play a significant role in the stability of the system. Damping of the low frequency oscillations specifically inter area oscillations is a major challenge faced by power engineers. The inter area mode of oscillation have frequency in the range of 0.1 to 0.8 Hz [1]. These oscillations are due to the dynamics in power transfer through the weak tie line or power flow that exceeds the transmission strength of these tie lines. Researchers have proposed methods for damping these oscillations by various means such as power system stabilizers (PSS) [2], superconducting magnetic energy storage device (SMES) [3], various FACTS devices specially series FACTS devices like SSSC, TCSC [4]. FACTS devices installed in the system for dynamic voltage regulation and enhanced power flow when equipped with properly designed damping controllers can be used to damp out inter area oscillations. These controllers installed in the system should perform as required from the first day of operation. This testing can be done only with hardware-in-loop (HIL) testing, for which the power system must be operating like the actual system i.e. real time simulation has to be carried out.

The objective of this paper is to design, implement and HIL testing of STATCOM controller for damping inter area oscillations. The validation of the controller has to be done on actual system. It is very rarely allowed to perform such validation test on the field. Hence, for validating the controller performance the actual like system is reproduced in the RTS which is RT-linux. The controller is implemented using DSP and interfaced with RTS using DAC-ADC combination. Section II describes the model of the power system and STATCOM. It also discusses the control strategy of the STATCOM. Section III demonstrates the real time station. Section VI gives the simulation results, and section V the conclusion.

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II. System model

A. Power System Model

The power system can be represented by a set of differential equations corresponding to the synchronous machines in the system and a set of algebraic equation representing the network. In this paper generators are represented by 1.1 model [5], where the machine consist of three phase armature winding on the stator and two windings on the rotor, one is field winding on d-axis and the other is damper winding on the q-axis.

The machine equations are:

$$\frac{dE_q^{'}}{dt} = \frac{1}{T_{d0}^{'}}\left[-E_q^{'} + (x_d - x_d^{'})i_d + E_{fd}\right] \cdots\cdots\cdots (1)$$

$$\frac{dE_d^{'}}{dt} = \frac{1}{T_{q0}^{'}}\left[-E_d^{'} - (x_q - x_q^{'})i_q\right] \cdots\cdots\cdots (2)$$

$$2H\frac{dS_m}{dt} = T_m - T_e - D(S_m - S_{m0}) \cdots\cdots\cdots (3)$$

$$\frac{d\delta}{dt} = \omega_B\left[S_m - S_{m0}\right] \cdots\cdots\cdots (4)$$

$$T_e = E_d^{'}i_d + E_q^{'}i_q + (x_d^{'} - x_q^{'})i_d i_q \cdots\cdots\cdots (5)$$

The network algebraic equation is

$$I = YV \cdots\cdots\cdots (6)$$

The non state variables i_d and i_q can be derived from the stator algebraic equations

$$E_q^{'} + x_d^{'} i_d - R_a i_q = v_q \cdots\cdots\cdots\cdots (7)$$

$$E_d^{'} - x_q^{'} i_q - R_a i_d = v_d \cdots\cdots\cdots\cdots (8)$$

The block diagram in Fig. 1 shows the way the system is solved.

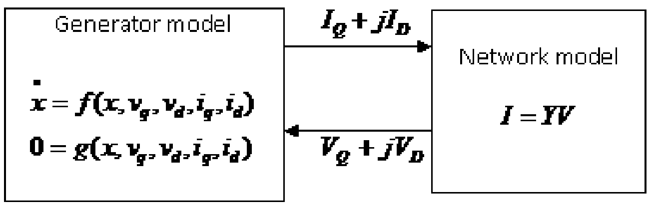

Fig. 1. Schematic diagram of the system

B. STATCOM Model

STATCOM is a second generation FACTS device based on voltage source converter using self commutating power semiconductor device such as GTO. The STATCOM consist of a shunt branch connected through a dc capacitor. This branch can transfer reactive and active power. An equivalent circuit for the STATCOM is shown in Fig. 2.

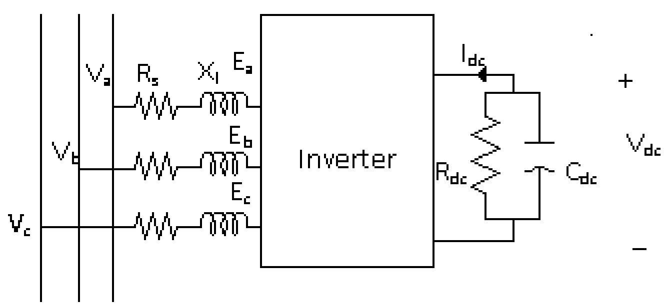

Fig. 2. Equivalent circuit of STATCOM.

The loop equation for the ac circuit may be written as

$$\frac{di_{abc}}{dt} = -\frac{R_s}{x_l} i_{abc} + \frac{1}{x_l}(E_{abc} - V_{abc}) \cdots\cdots\cdots\cdots (9)$$

Where R_S and x_l represent the STATCOM transformer losses, E_{abc} the inverter ac side phase voltage, V_{abc} the system side phase voltage, i_{abc} are the phase currents.

$$where\ E_{abc} = kV_{dc}\cos(\alpha + \omega t) \cdots\cdots\cdots\cdots (10)$$

V_{dc} is dc capacitor voltage; k is the modulation gain, α the injected voltage phase angle.

Consider the equation for the dc side of the inverter, we obtain,

$$C_{dc}\frac{dV_{dc}}{dt} = \frac{V_{dc}}{R_{dc}} + i_{dc} \cdots\cdots\cdots\cdots (11)$$

We use Kron's transformation to the D-Q-O variables

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\omega_B t & \sin\omega_B t & \frac{1}{\sqrt{2}} \\ \cos(\omega_B t - \frac{2\pi}{3}) & \sin(\omega_B t - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \cos(\omega_B t - \frac{4\pi}{3}) & \sin(\omega_B t - \frac{4\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_D \\ i_Q \\ i_0 \end{bmatrix} \cdots\cdots (12)$$

Thus STATCOM can be modeled by these state equations in the DQ variables [6].

$$\begin{bmatrix} \frac{di_{DS}}{dt} \\ \frac{di_{QS}}{dt} \\ \frac{dV_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R\omega_B}{x_l} & -\omega_B & A_{13} \\ \omega_B & -\frac{R\omega_B}{x_l} & A_{23} \\ A_{31} & A_{32} & -\frac{\omega_B}{b_c R_{dc}} \end{bmatrix} \begin{bmatrix} i_{DS} \\ i_{QS} \\ V_{dc} \end{bmatrix} + \begin{bmatrix} -\frac{\omega_B}{x_l} & 0 \\ 0 & -\frac{\omega_B}{x_l} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} V_{DS} \\ V_{QS} \end{bmatrix} \cdots\cdots (13)$$

$$A_{13} = \frac{\omega_B k\sin(\alpha + \theta)}{x_l} \qquad A_{23} = \frac{\omega_B k\cos(\alpha + \theta)}{x_l}$$

$$A_{31} = -\frac{\omega_B k\sin(\alpha + \theta)}{b_c} \qquad A_{32} = -\frac{\omega_B k\cos(\alpha + \theta)}{b_c}$$

The reactive and active currents can be mathematically defined as

$$i_P = i_{DS}\sin\theta + i_{QS}\cos\theta \cdots\cdots\cdots\cdots (14)$$

$$i_R = i_{DS}\cos\theta - i_{QS}\sin\theta \cdots\cdots\cdots\cdots (15)$$

C. STATCOM Control Strategies

For damping the inter area oscillations the real power transfer through the tie line has to be controlled [7]. This can be done in STATCOM only when k and α are controlled together i.e., Type I control strategy has to be applied. The block diagram of the control strategy is given in the Fig. 3.

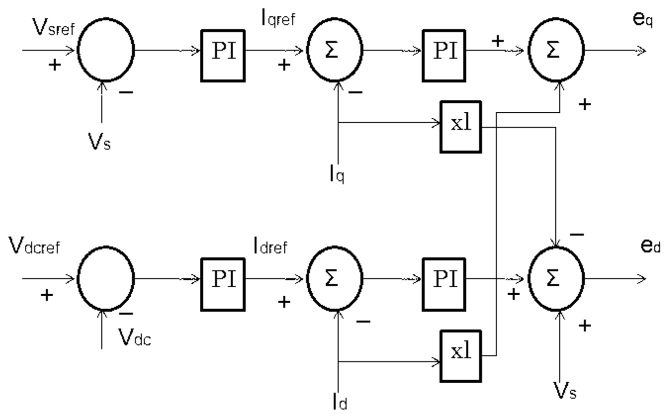

Fig. 3. Block diagram of Type I control strategy of STATCOM.

One of the major technique used in designing the controller is H∞, this technique of controller design is having the advantage that it can be applied to problems involving multivariable system with cross coupling. In this technique objective function is formulated according to the application and the control problem is expressed as a mathematical optimization problem. The controller that satisfies the objective function is the solution. H∞ technique has been used in the controller design in power systems for various applications for past decade [8]-[10]. In large power systems the reduced system model is first found and then the controller is designed by formulating the objective function.

III. Real time station

"Real time" is an often used but ill-defined term. Hard real time is a precise term which refers to processes with timing deadline that cannot be missed. Typically, for accurate simulation of power system transients where low frequency electromechanical oscillations are concerned a time step of about 1-10ms is required [4], [11]. There is another challenge faced by real time simulation which is scalability. If it is needed to analyse the interaction between several control systems and the power system we need to break up the system into several linked subsystems and has to be distributed to different processors for its simulation. In such a case special care has to be taken for the inter processor communication.

There is a variety of real time simulators each having advantages and disadvantages. The disadvantages are price, platform restriction and nonstandard Application Peripheral Interface (API's). Linux which is freely available and extensively tested operating system is a perfect platform for extending into real time category. RTLinux is one of the best choices for real time Linux solution. RTLinux inserts a small real time kernel below the standard Linux kernel and treats the Linux kernel as one of the real time process. The disadvantage of this approach is that the real time tasks operate in kernel space and in case of software bug they may cause substantial harm. RTLinux solves the unmaintainable error which has catastrophic effect when RT codes are mixed with non RT codes. This is done by decoupling the RT and non RT software components.

Anything that requires strict timing restriction should be written as a thread or signal (interrupt) handler and anything that doesn't need hard real time should go through regular linux. RTLinux supports real time interrupt handler and real time periodic tasks with interrupt latencies. RTLinux give worst case interrupt latencies of less than 15 microseconds on a standard x86 PC. RTLinux runs Linux as its lowest priority thread and provides access to full power of Linux through a variety of communication methods. Fig. 4. shows the basic architecture of RTLinux.

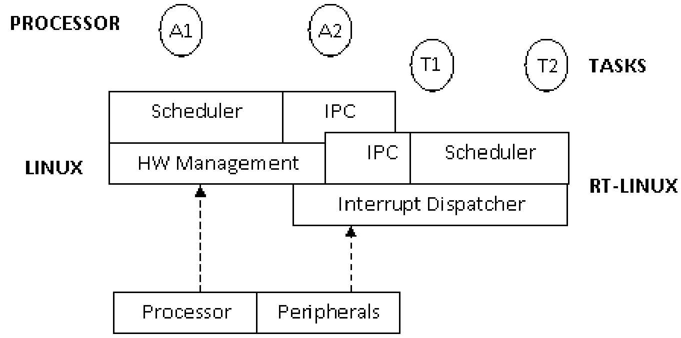

Fig. 4. Architecture of RTLinux.

A PC-DSP based real time control system can efficiently implement the control strategy for the STATCOM [12]. It includes a host PC operating in RTLinux which simulates the power system and the STATCOM in real time and a DSP along with the interface boards to implement the controller for damping the inter area electromechanical oscillations. The communication between the DSP and the master PC is via a industry standard architecture (ISA) bus. PC provides the offline simulation of the power system and FACTS controller. It also provides real time monitoring, coordination and protection for the DSP based subsystem.

IV. Simulation results

The power system transients for low frequency electromechanical oscillations in a Kundur system consisting of 4 machines, 10 buses as shown in Fig.5. is considered.

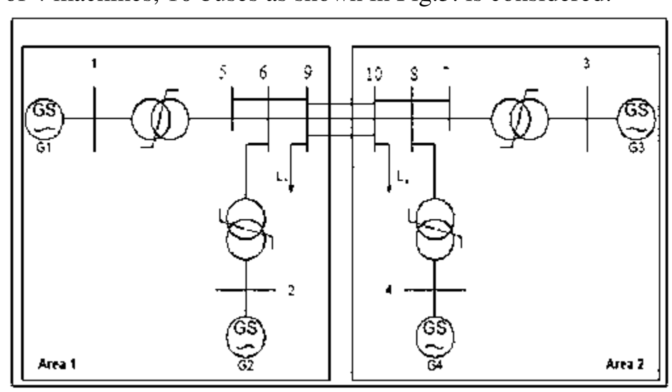

Fig. 5. The test system.

The inter area oscillations can be damped out by controlling the real power transfer through the network. With the development in the emerging FACTS controllers we can control the real and reactive power flow. STATCOM which is a shunt device can control the real power exchange if both the modulation gain and the injected voltage phase angles are controlled, i.e. when the type I control strategy is applied. The control strategy based on artificial intelligence, genetic algorithm etc. need field testing for tuning and learning, but in real life it is not possible since it is costly, risky and also the load variation can be unpredictable.

The integration of the controller can be done in three different methods [13]. The first method applies when the controller is in the developing process, here the controller can be implemented on an embedded computer and the communication with the simulated system can be done using software signals, Ethernet message, remote procedure calls etc. The main advantage here is that no DAC/ADC set is required. In second method, both the controller and the system are simulated on the same computational platform. The last method which is the best method for validating the controller is where the independent controller device is interconnected with the simulated environment using analog and digital signals.

The type I PI controller for STATCOM can be implemented using TMS322F2812 DSP [14]. This is a 16-bit fixed point DSP but minimizes the truncation problem due to overflow since it has a 32-bit accumulator and product register. The implemented controller can be tested against the emulated system in RTLinux.

The power system is to be simulated in real time for various fault conditions in RTS, and the performance of the system for the transients are analysed with and without the designed controller. The controller is to be implemented on DSP and interface boards. The hardware in loop testing of the controller will be performed using the emulated power system on RTS. The control signal from DSP is fed back to the simulated system via DAC-ADC combination, as shown in Fig. 6.

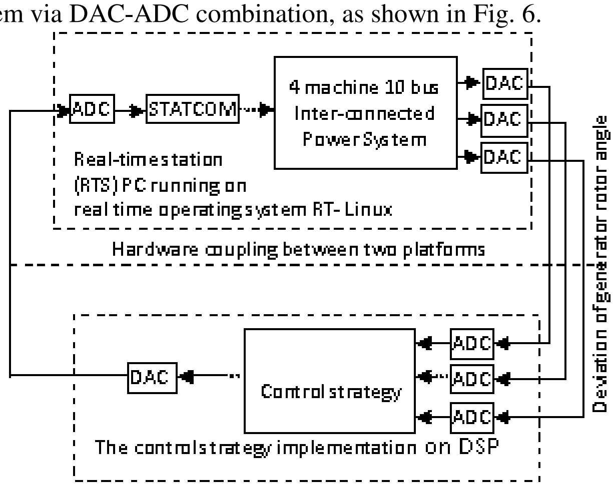

Fig. 6. Closed loop configuration.

One of the severe disturbances that excite poorly damped inter area oscillation is three phase fault. Change in load, change in generation, change in power flow, etc. are disturbances that are less severe compared to the faults and are not considered here. The system was simulated without any disturbance and with the faults in various lines. The STATCOM was introduced into the system and found that the performance of the system remained the same at steady state. When transient conditions were considered the stability of the system showed an improvement with the STATCOM in the system. Fig. 7 shows the response of the system at steady state with the STATCOM in the system.

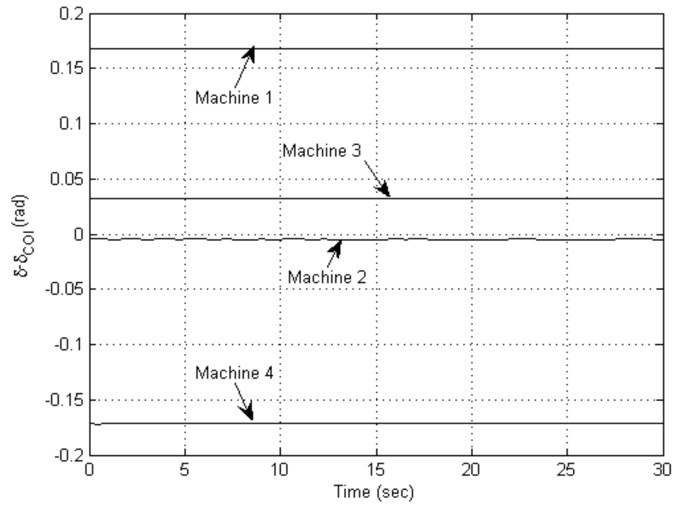

Fig. 7. The response of the system at steady state with the STATCOM

The simulations were carried out for some of the probable three phase fault scenario. The following outages were considered with a clearing time of 1.5 sec:

- Fault in line 5-6
- Fault in line 6-9.
- Fault in line 9-10.
- Fault in line 8-10.
- Fault in line 8-7.

It was found that the fault in line 7-8 is the most severe. The response of the system for this fault without and with STATCOM i.e. the deviation in the phase angle of the generator with respect to the reference center of inertia is shown in Fig. 8. and Fig. 9. respectively. It is found that the deviation in the angle increases with the time; hence the system is unstable following the fault. And the STATCOM brings the system to the stable state.

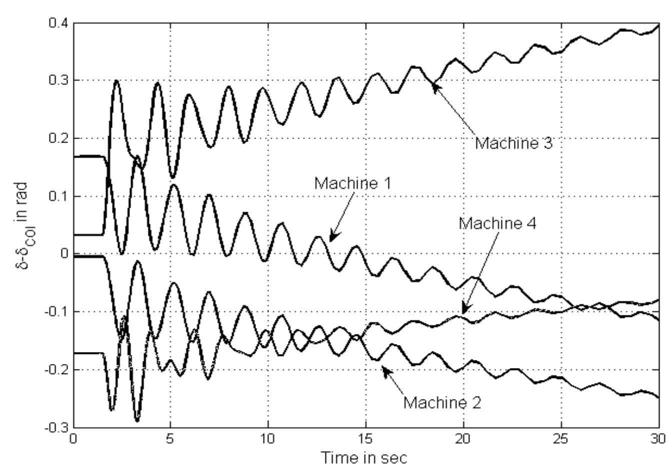

Fig. 8. The response of the system for a fault in line 7-8 without STATCOM

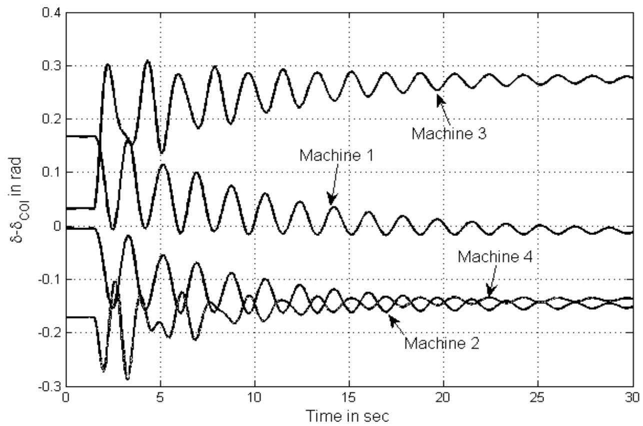

Fig. 9. The response of the system for a fault in line 7-8 with STATCOM

The reactive power injected by the STATCOM to the system without any fault remains at zero when the reference voltage is equal to the steady state value of 0.975p.u. When the fault occurs in line 7-8 the reactive power injected varies such that the bus voltage is regulated to the reference value. The variation in reactive power injected by the STATCOM without any fault and with the fault in line 7-8 is shown in fig. 10. Fig. 11 shows how the bus voltage is regulated by the STATCOM when the fault occurs in the line.

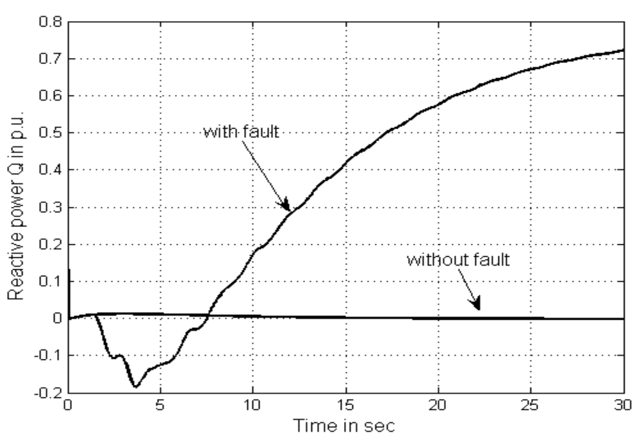

Fig. 10. STATCOM injected reactive power into the system

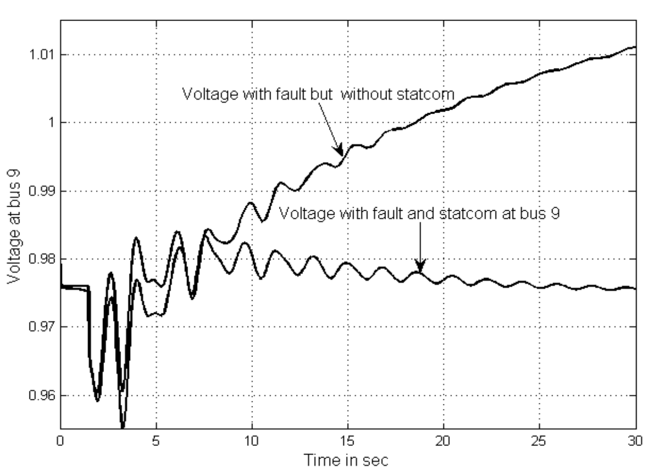

Fig. 11. Voltage at bus 9 of the system

The real power injected by the STATCOM without any fault remains at a constant negative value depending on the dc capacitor voltage reference. When the fault occurs in line 7-8 the real power absorption varies such that the dc capacitor voltage is regulated to the reference value (V_{dcref}=1.5 p.u.). The real power absorbed is utilized for compensating for the losses in the dc capacitor.

The variation in real power absorbed by the STATCOM without any fault and with the fault in line 7-8 is shown in fig. 12. Fig. 13 shows the regulated dc capacitor voltage.

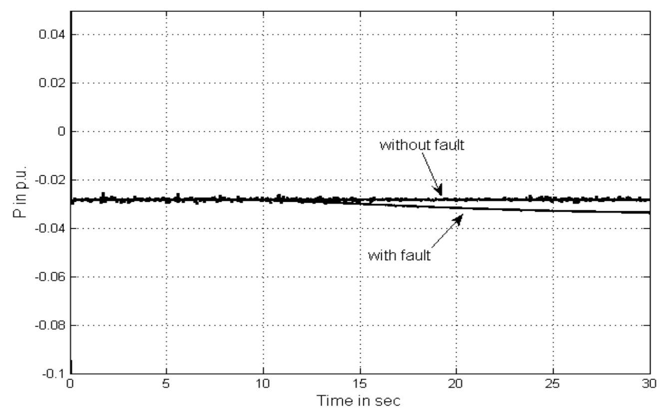

Fig. 12. STATCOM real power exchange to the system

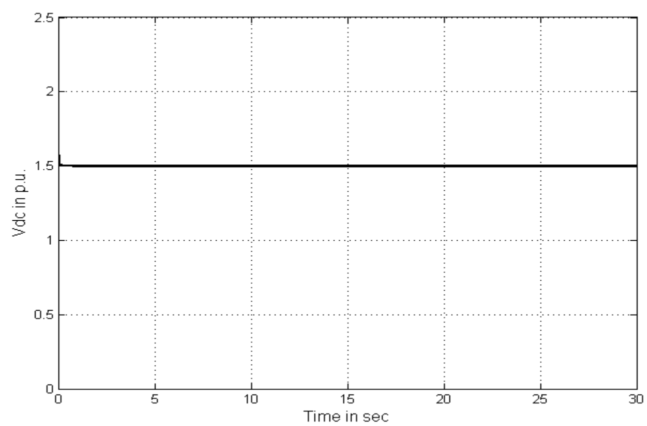

Fig. 13. STATCOM dc capacitor voltage

Similar is the case for fault in line 10-8, here the severity of the fault is less, the response is shown in Fig. 14. and Fig. 15. without and with STATCOM in the system.

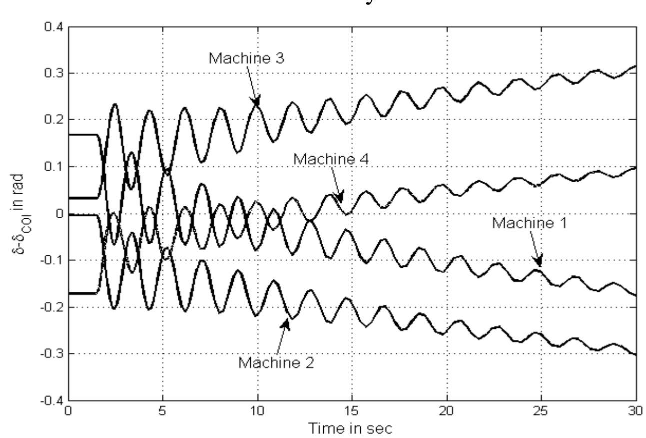

Fig. 14. The response of the system for a fault in line 10-8 without STATCOM

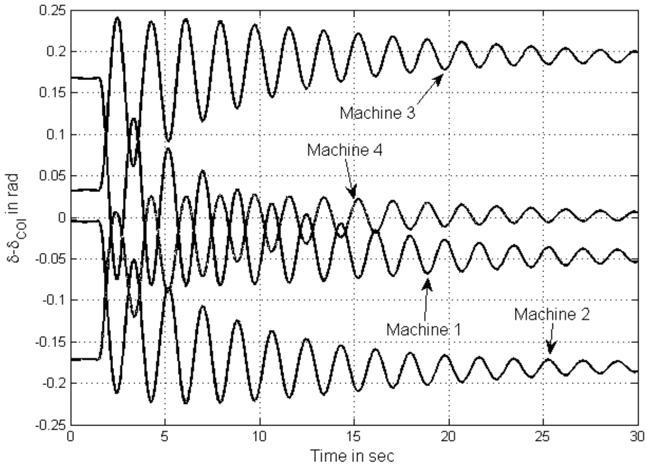

Fig. 15. The response of the system for a fault in line 10-8 with STATCOM

V. CONCLUSIONS

The paper investigated the improvement of transient stability of an interconnected system using STATCOM which is a shunt FACTS device. The inter-area oscillations can be controlled by changing STATCOM's bus voltage angle and magnitude, hence regulating active power flow through the network. The transient stability can be improved by introducing a STATCOM in the system. The Type I control strategy of STATCOM can be implemented using Digital Signal Processor (DSP) TMS322F2812. The hardware in loop simulation of controller is found to be better than the other methods of integration of the controller. The hardware in loop testing of the controller can be performed using the emulated power system on RTS which is a PC based on RTLinux. The closed loop testing not only tests the functionality and setting of the controller, but also tests the systems reaction to the device operation.

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